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Automotive Fuels
at Low Temperatures
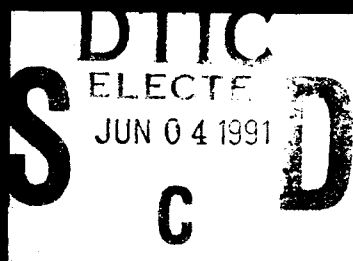
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**US Army Corps
of Engineers**
Cold Regions Research &
Engineering Laboratory

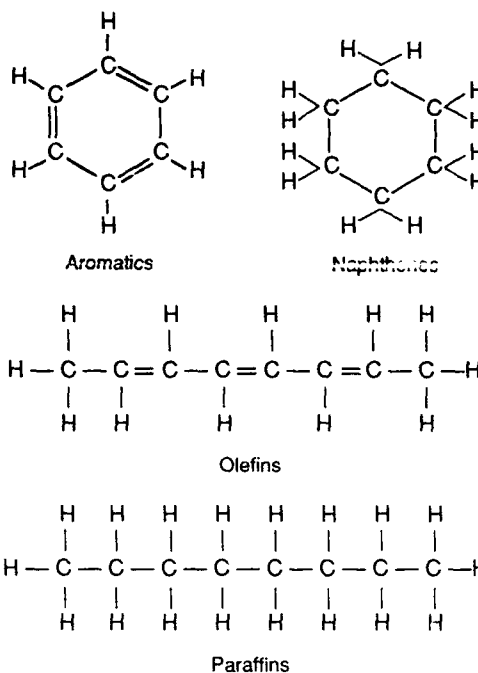# Automotive Fuels at Low Temperatures

Deborah Diemand

Introduction

Problems with fuels at extremely low temperatures are largely due to wax formation, increased viscosity, decreased volatility and contamination by water. This is especially true of diesel fuels, but even gasoline suffers from these problems to some extent. Some difficulties may begin to appear at temperatures above 0°C. The overwhelming majority of fuels are derived from petroleum crude oils. Straight-run fuels are produced through primary distillation of these crude oils. In addition, secondary processing of the crude produces further fuel stocks from other fractions that could not otherwise be used as fuel. Cracking reduces large molecules into smaller fragments, which may be used in the lighter fuels such as gasoline; alkylation produces larger molecules from light gases or from the lighter products of the cracking process; polymerization is similar to alkylation but results in products with a lower octane rating; reforming catalytically alters certain low-octane substances, resulting in a high-octane product.

Chemical composition

There are four basic molecular structures in petroleum oil products, as shown in Figure 1: aromatics, naphthenes, olefins and paraffins.

Aromatics are compounds containing benzene ring structures. Aromatic compounds may contain one to many of these unsaturated rings as well as naphthene ring structures and branched or straight-chain paraffins and olefins replacing one or several of the hydrogen atoms in the benzene ring. These compounds tend to cause swelling and degradation of certain rubbers and sealants. For this and other

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Aromatics   Naphthenes

Olefins

Paraffins

1. Four basic molecular types present in petroleum products.

reasons, the maximum acceptable concentration of aromatics in turbine fuels is 20–25%. The aromatics content of straight-run fuels is about 10–20%.

Naphthenes are compounds containing saturated carbon rings. The molecule shown in Figure 1 represents cyclohexane, which is a common component of petroleum oils. These ring structures may have any number of carbon atoms, but five or six are most common. Naphthenes may have a number of ring structures and paraffin or olefin side chains but no aromatic components. Lubricating oils made from naphthenic crude oils have a lower specific gravity and a lower pour point then similar oils made from paraffinic crudes.

Olefins are composed of unsaturated carbon chains. These may contain any number of unsaturated bonds and may be branched or unbranched, but they contain no ring structures. Olefins are common in cracked fuels but are seldom present in crude oils. Their unsaturated bond(s) result in their being more or less unstable, and their presence in fuels may result in a degree of gum or varnish formation or in other undesirable characteristics.

Paraffins are composed of saturated carbon chains. These may be branched or unbranched, but they contain neither unsaturated bonds nor ring structures. Paraffins and naphthenes are common constituents of low-molecular-weight distillation products. The heavier molecules in the paraffin group constitute the paraffin waxes.

Crude oils are extremely complex mixtures of these organic compounds, with varying amounts of sulfur, nitrogen, oxygen and trace me'als. The proportions of these compounds vary enormously between crude oils from different sources, as do the proportions of the various fractions separated during the distillation process. In this process the crude is heated to about 400°C and fed into a fractionating tower, where it instantly vaporizes. The vaporized compounds then rise through a negative temperature gradient in the tower and condense when they reach a section where the temperature is less than their boiling points. The condensate is collected in trays and drawn off for further treatment to produce the desired final product. Thus, the lubricating oil fractions are drawn from the bottom of the column, followed by the heavier fuel oils, diesel fuel, kerosene and jet fuels, and finally gasoline from the top of the column. Figure 2 shows the distillation range for the various fractions, as well as their relative proportions in an average crude, which, as mentioned previously, can vary greatly. For example, the percentage of the gasoline fraction distilled from the crude may be as low as 2% or as high as 50%.

In general, diesel fuel is a straight-run distillation product with little additional processing except for the addition of such compounds as cetane improvers, anti-icing agents, corrosion inhibitors and so forth. In the case of gasolines and jet fuels, however, further treatment of these preliminary distillation products may include cracking, alkylation, polymerization and reforming.
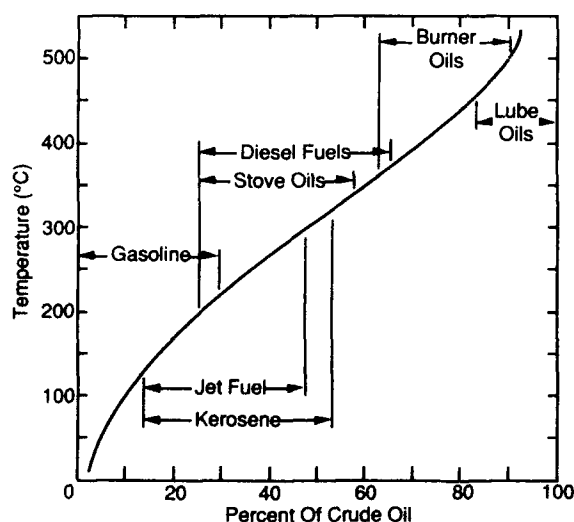
2. Distillation ranges and percentages of recovered product from an average crude oil. Note the considerable overlap in the middle distillation range including kerosenes, jet fuels and diesel fuels. This competition for the same fraction of the crude barrel may result in high prices or short supplies of one or more of these products.

Table 1. Fuels commonly used in cold regions. DF-2 is included for comparison. Values given are typical unless otherwise noted.

	Automotive gasoline*	Aviation gasoline	JP-4	Jet B	JP-5	Jet A	Jet A1	JP-8	DF-A	DF-1	DF-2
Density (kg/m³)				0.7507†		0.7753†	0.7753†	0.8232		0.850	0.8524
°API	~64		45–57	57†	36–48	37–51†	37–51†	37–51‡		42	34.5
Flash point (°C)	<–45				62 60**	38	38	46, 38**	38††	38††	52††
Cloud point (°C)								–54	–51†	–51	–12
Pour point (°C)									–57‡‡	–51	–40
Freezing point (°C)	~–60	–58†	–62	–62, –50†	–49	–45, –40†	–51, –47†	–54, –50‡‡			
Viscosity (cs)											
40°C		0.52	0.65	0.75	1.3	1.2	1.2	1.5	1.1–2.4***	1.3–2.4***	3.6
–20°C		1.4	1.7	1.7	4.3	4.3, 8†	4.3, 8†	4.3, 8‡‡		1.3–2.9‡	1.9–4.1***
Distillation volume (°C)											
10%	50†	64,75†	93	93	199	190,204†	190,204†	190,186‡‡		179	172
50%	77,110†	104,105†	148	148,188†	219	212	212	212		213	236
90%	110,185†	126,135†	219	219	240	250	250	250	288†	251,288†	289,338†
End point	185,225†	158,170†	246	246,243†	260	266,300†	266,300†	266,330‡‡	330,300†	272,330†	347,370‡
Vapor pressure (kPa) @ 38°C (100°F)	103†	47	18	18, 21†		<1	1.4	1.4	0.6		
Heat content (Btu/gal)	115,000	118,000			125,000			125,000		134,000	138,000

* Volatility class E
† ASTM specified maximum
‡ MILSPEC range
** MILSPEC minimum
†† ASTM specified minimum
‡‡ MILSPEC maximum
*** ASTM specified range

Fuel properties

The fuel properties discussed in this section are those given in Table 1 for various fuels commonly encountered in cold regions.

The density of the fuel reflects the size of the constituent molecules and consequently some related properties. In general, lower density implies higher volatility, lower freeze or pour point, lower flash point, lower viscosity and higher vapor pressure. The energy content per unit volume (i.e. Btu/gal) usually increases as the specific gravity increases or the API gravity decreases. This change in energy content usually translates into an increase or decrease in fuel consumption or power output of the engine, depending on the engine design.

The flash point is the temperature at which the fuel's vapor will ignite in the presence of a spark and is primarily an index of the flammability hazard posed by the fuel. The fire point, seldom given in technical information, is a higher temperature at which combustion will be sustained.

The cloud point is the temperature at which wax crystals will begin to form in diesel fuel as the heavier molecules begin to precipitate out of solution. The value specified should be 6°C above the lowest temperature likely during the month. The pour point is the temperature at which the oil will barely flow. In general, a fuel cannot be used below its cloud point. In contrast to diesel fuels, there is such a small spread between the cloud point and the pour point of jet fuels as to make these two determinations pointless. The freezing point, usually given for jet fuels and gasolines to indicate their low-temperature limits, is the temperature at which crystals form in a chilled solution that is being stirred.

The viscosity influences the degree of atomization of the fuel upon injection into the combustion chamber and therefore how well it burns. The fuel must be thick enough to protect engine parts but thin enough to flow readily and burn smoothly and completely. Caterpillar recommends for its diesel equipment that if the fuel viscosity is above 1.4 cs at 40°C, the fuel can be used yearround, while if the viscosity is below 1.4 cs at 40°C, it should only be used below 0°C. Further, fuels with a viscosity lower than 1.2 cs at 40°C should not be used at all in diesel engines.

The distillation volume figures represent the temperature at which 10%, 50% and 90% of the fuel will boil off. The end point is the temperature at which no fuel remains. Engine manufacturers often spe ify a maximum end point temperature for the fuel recommended for use in their engines. This temperature reflects the combustion chamber temperature expected under normal operating conditions. In extremely cold conditions, therefore, a fuel with a relatively low end point should be used. The distillation range of

3. Boiling ranges of various types of fuel.
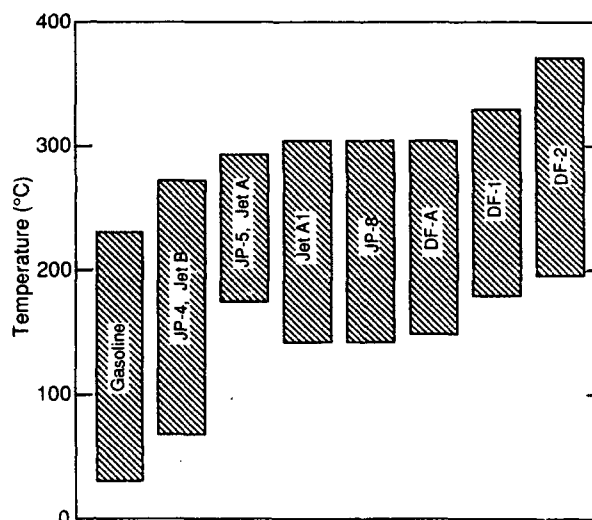
fuels, also shown graphically in Figure 3, gives an idea of the molecular weights of compounds present in the fuel. The lighter, more volatile compounds will boil off at the lower temperatures of the 10–50% levels, while the heavier ones will not boil until a much higher temperature. Thus, a lower temperature at any of the levels implies a lighter, more volatile fuel, while the spread between the 10% level and the end point reflects the width of the distillation range from which the fuel is drawn and incidentally the relative amount that can be obtained from the parent crude oil. Jet B and JP-4 are called "wide cut" fuels because they contain low-molecular-weight compounds with boiling points about 100°C less than the lightest fractions of the kerosenes, while their end points are only 20°C lower than those of the kerosenes. This is easily seen in Figure 3.

The vapor pressure of a fuel reflects its volatility. A high vapor pressure is useful and desirable in gasolines but is not necessary and may indeed be hazardous in kerosene and diesel fuels. The volatility of gasoline is its single most important property at low temperatures. An extensive test program sponsored by the American Petroleum Institute showed that a reduction in vapor pressure from about 90 kPa to about 60 kPa resulted in significant deterioration in the performance of 19 of the 51 vehicles tested and noticeable deterioration in most of the rest (Abramo et al. 1989).

Octane numbers are an index of the ignition performance of gasoline and reflect its tendency to knock. Knocking, also called pinging, preignition or surface ignition, is an abnormal combustion

condition resulting in a characteristic sound produced by premature ignition of part of the fuel–air mixture in the combustion chamber. This may be the result of either compression ignition or hot spots in the combustion chamber caused by deposits, by spurs or sharp corners in the block casting, or by excessively hot spark plug electrodes. In any case the combustion is much more rapid than normal and places very large, abrupt loads on the cylinders, rods, etc. This is what causes the knocking sound. This and other abnormal ignition conditions can seriously damage an engine. The functional difference between low- and high-octane gasolines is that higher-octane fuels are more resistant to premature ignition at higher temperatures and compressions and consequently to knocking. They are therefore recommended for use in high-compression, high-performance engines.

The octane rating system is an arbitrary system based on the performance of the gasoline in a standard engine compared with the performance of a mixture of heptane, which has a strong tendency to knock, and iso-octane, which resists knocking. The octane rating number reflects the percentage of iso-octane in the mixture with the same knocking characteristics as the gasoline being tested. A higher octane rating implies a higher ignition temperature and a slower burning rate and thus lower knocking tendency. Octane ratings above 100 are calculated by comparing the performance of the unknown gasoline with iso-octane containing various concentrations of tetra-ethyl lead. Thus, a gasoline with an octane rating of 120 will have the same knock characteristics as iso-octane with a concentration of about 0.2 mL of tetra-ethyl lead per gallon.

The ignition performance of diesel fuels is rated by cetane number. In contrast to the octane rating system, in which a higher number reflects a diminished self-ignition tendency, an increase in the cetane number implies an increased self-ignition tendency and therefore greater ease of combustion under compression. Again, the rating system is based on the performance of the diesel fuel in a standard engine compared with that of a mixture of two standard compounds, in this case cetane and heptamethylnonane. The cetane number is the percentage of cetane in the standard mixture whose ignition performance is the same as that of the unknown fuel.

Low-temperature fuels

Table 1 shows some of the properties of fuels commonly encountered in cold regions (as well as those of DF-2 for comparison, although this fuel is seldom used in very cold conditions). Figure 3 shows the boiling ranges of these fuels. The gasolines are the lightest of these fuels and will be discussed later. Jet B and JP-4 are virtually identical and are used in jet or turbine engines. They are

essentially a 50:50 mixture of heavy naphtha fraction (like gasoline) and kerosene. They cannot be used in gasoline engines because of their low octane rating, and they are unsuitable for use in diesel engines because of their low cetane rating.

JP-5, JP-8, Jet A, Jet A1 and DF-A are all kerosenes. They are composed chiefly of paraffins and naphthenes. These are very stable and will not readily react with elastomers, paints and so forth. In addition the naphthenes have very low freezing points and therefore impart good low-temperature properties to the fuels.

Jet A1, JP-8 and DF-A (arctic-grade diesel fuel) are virtually indistinguishable, the only difference between them being the nature of the additive package. JP-8 contains a corrosion inhibitor, an anti-icing agent and an anti-static compound. These may or may not be present in Jet A1. JP-8 is being considered by the military as a single fuel for all jet and turbine aircraft and diesel engines involved in its combat operations. The use of a single fuel will simplify transport, storage and refueling operations and will eliminate problems of inadvertent use of inappropriate fuel. It is reportedly superior to diesel fuel with regard to fuel-related corrosion, engine wear and engine oil contamination owing to its lower sulfur content and more complete combustion than diesel fuel. On the whole this fuel appears to hold much promise for use in cold regions in spite of its relatively high pour point, which is 10°C higher than that of DF-A at –57°C. Jet A1 is often relabeled and supplied by fuel distributors as DF-A. Many of the problems associated with the use of light fuels in diesel engines are the result of low viscosity and lubricity, which can cause premature wear of fuel pumps and injector systems. However, these problems, if they exist at all, will be insignificant in cold regions since fuel temperatures will not normally be high enough to reduce the fuel viscosity to levels below those normally found in standard diesel fuels at normal operating temperatures.

Jet A and JP-5 are similarly indistinguishable. Jet-A is used by the major U.S. airlines for domestic flights, while Jet A1 is used by overseas carriers and U.S. airlines on overseas flights. These differ only in that Jet A1 has a lower freeze point. JP-5 is used for safety reasons by the U.S. Navy because of its high flash point, and it may be used as diesel fuel.

DF-1 is winter-grade diesel fuel and will be discussed later.

Other fuels that may at first glance appear suitable for low-temperature use are propane and gasohol; however, problems are likely with both of these. The boiling point of propane is –4.5°C and its vapor pressure at about –20°C is too low for effective fuel delivery in most equipment set up to use propane. The problem with

gasohol is due first to the marginal miscibility of alcohol with gasoline and second to the hygroscopic nature of alcohol. If too much water is taken up by the alcohol by exposure to moist air or condensation, it will tend to come out of solution, forming a layer of alcohol and water at the bottom of the fuel tank. This must be drained off since the engine will not run on this mixture.

On the whole, there are few problems with gasolines at low **Gasoline** temperatures, and these are mostly associated with their dissolved water content and with lowered volatility of the gasoline at very low temperatures. The pour point of gasoline is well below the temperature at which it is feasible to operate a machine for other reasons, and the very modest amount of heating required to warm batteries and engine oil to ensure successful starting is enough to assure adequate fuel volatility for combustion in most cases, especially in fuel-injected engines. Carbureted engines may experience some difficulty until the engine warms somewhat.

Distillation products that compose gasoline boil off immediately after the light gases at temperatures from about 40° to 200°C and include butane and other compounds with carbon numbers up to about nine, including any or all of the basic molecular types described earlier. The octane rating of such straight-run gasolines is usually low, and in the past tetra-ethyl lead was commonly added in small quantities as an antiknock compound. The unleaded fuels in common use today do not contain antiknock compounds, and therefore a higher-octane base stock must be used to achieve the higher octane ratings required by modern high-performance engines. These are obtained by blending the straight-run product with varying proportions of synthetically manufactured base stocks. These are produced largely through catalytic cracking of the heavier fractions of the crude oil and subsequent alkylation, resulting in the formation of highly branched paraffinic hydrocarbons (like iso-octane) and low-molecular-weight aromatics that have intrinsically high octane ratings, such as benzene and toluene. These are frequently present in relatively high concentrations in gasolines for this reason. In rare instances, benzene may be present in sufficiently high concentrations to cause problems at low temperatures. This is because the melting point of benzene is very high (5.5°C), causing it to solidify at temperatures higher than normal for gasolines. Normally the presence of other compounds, such as toluene (with a melting point of –95°C), counteracts this tendency by keeping the benzene in solution.

Gasoline blends vary seasonally to ensure that they have satisfactory volatility characteristics in cold weather and are not prone to

4. The 10% distillation temperature of gasolines reflects their starting performance at low temperatures. (After Smolin 1968.)
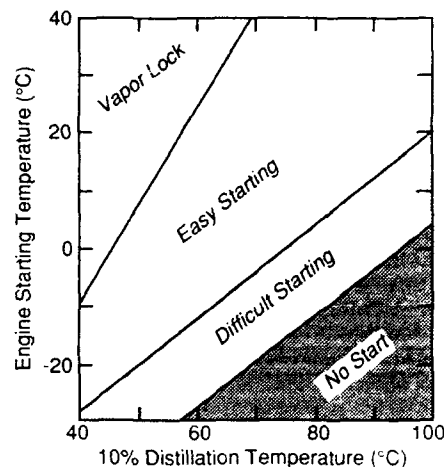
vapor lock (discussed below) in warm weather. The ASTM standard for automotive gasolines specifies five volatility classes, each with its own set of physical properties. The specifications for volatility class E are shown in Table 1 and reflect the properties of gasolines to be used in cold regions or cold seasons. The other four volatility classes are heavier and less volatile than this.

Usually the winterization of gasoline involves the addition of butane to the base stock to produce a cold-weather fuel. Vapor lock is encountered when the gasoline in the fuel pump or lines is heated to a point where the lighter fractions begin to boil. This causes bubbles to form, which hinder or stop the flow of gasoline to the engine. This problem will not usually occur in cold regions; however, it may if fuel blended for extremely cold regions is used in warm conditions. Such conditions are sometimes encountered in the early spring in areas with cold winters, such as New England. An unusually warm day in a normally cold month, or an abnormally early warm period before winter gasoline stocks are exhausted, is enough to cause a few cases of vapor lock.

The 10% distillation temperature may be used as an indication of gasoline performance at various ambient temperatures. As shown in Figure 4, a gasoline suitable for use in warm weather will not be sufficiently volatile at low temperatures, while a low-temperature fuel may cause vapor lock in warm conditions.

Automotive and aviation gasolines differ in several regards. First, aviation gasolines are leaded, while most automotive gasolines are not. Using a leaded fuel in a vehicle designed for unleaded fuel will destroy the platinum catalytic material in the catalytic converter and possibly increase deposits in the combustion chamber. Second,

aviation gasoline is a slightly heavier mixture than automotive gasoline, with a vapor pressure about half that of automotive gasoline. This is to prevent vapor lock in aircraft and will almost certainly result in unsatisfactory performance in automotive equipment. Third, most aviation gasolines have a higher octane rating than most automotive gasolines. This may cause delayed ignition problems in automotive equipment. In short, it is not a good idea to interchange these two types of gasoline.

Both gasoline and diesel fuels are able to dissolve about 0.1% water at relatively high temperatures. At very low temperatures this water comes out of solution in the form of ice crystals, which may obstruct fuel systems. This can be avoided by adding to the fuel small proportions (0.3% or less) of low-molecular-weight alcohols. Heavier alcohols are less effective. In general, methanol is most effective as it can dissolve a larger amount of water per unit volume than higher-molecular-weight alcohols; however, ethanol or isopropanol should be used, if possible, in fuel-injected engines, as methanol may damage fuel injection pumps. Methanol is a strong solvent and may harden, crack or swell some seals and gaskets. It may also corrode certain aluminum and magnesium components. The heavier alcohols such as ethanol and isopropanol are less prone to cause damage of this sort, and for protection against the very small amount of atmospheric moisture present in extremely cold regions, these heavier alcohols should prove satisfactory.

Water contamination and its remedies

The more fuel in the tank, the smaller will be the volume of air from which moisture can be condensed. Therefore, vehicle fuel tanks should be kept full when not in use. Wipe all snow or ice from dispensing equipment and from around the fuel tank filling cap before removing the cap to refuel. Alcohol should be added to the fuel in the vehicle's tank and not in the fuel containers or storage drums. This is because alcohols are hygroscopic and will tend to draw moisture not only out of the fuel but also from the surrounding air, gradually becoming saturated and therefore ineffective after extended periods. It is best to add the alcohol when the tank is about half full and then finish filling the tank. This will effectively mix the two. After filling the tank, replace the cap securely. Do not use contaminated fuel.

Condensation problems will be most serious in vehicles that are taken into warm areas, such as garages, fairly often. Despite every effort to exclude water from the fuel tank, commonly a small amount of water collects in the bottom of the tank. Ultimately this will corrode the tank and in extreme cases can cause rust perforation. Neither detection nor remedy is trivial. The simplest method

is to siphon a small amount of fuel from the lowest point of the tank into a jar. If water is present, repeated samples should be taken until the amount of water is insignificant. Some fuel filters allow visual inspection of the fuel and may be used to detect the presence of water. This should be removed by siphoning or by removing the tank to empty it.

Safety precautions   Always ground a vehicle before refueling since static electricity buildup is common in extremely low temperatures due to the very low moisture content in the air. This can generate a spark between the fuel nozzle and the vehicle when refueling is begun. This can cause serious explosions. In addition, gasoline flowing over a surface generates static electricity, which can cause a spark unless means are provided to ground the electricity. Once the fuel is flowing, an effective ground is the metallic contact of the container or dispensing hose nozzle held firmly against the tank or container being filled. Many refueling facilities in cold regions provide a grounding strap, which should be connected to the tank or vehicle chassis before refueling.

Diesel fuel   There are a number of problems encountered in the use of diesel fuels in cold regions, including wax formation, solidification, excessive viscosity, excessive sulfur content and contamination with water.

Diesel fuels are composed of distillation products that boil off between about 200° and 350°C. These are heavier than gasolines and kerosenes and are composed mostly of distillation products. They are generally either a distillate blend, a distillate and kerosene blend, or a kerosene blend, depending on the grade of the fuel, i.e. winter grade (DF-1) or arctic grade (DF-A). In most cases, DF-A and some DF-1 fuels are essentially kerosene, similar to aviation turbine fuels such as Jet A or JP-8, and thus may be considered low-temperature fuels. Their chemical composition is heterogeneous, and their low-temperature behavior will be influenced by the nature of the crude oil from which they were distilled. The higher boiling components of diesel fuels are composed to a great degree of high-molecular-weight paraffins. They are abundant in No. 2 diesel fuel (DF-2), less so in No. 1 diesel fuel (DF-1). These are the waxes that are responsible for many of the low-temperature problems of diesel fuels. However, they also exert a beneficial influence. They have a higher heat content than the lower-boiling compounds, which translates into greater fuel efficiency. They impart a greater lubricity to the fuel, resulting in less wear in the fuel pump and other components. Because of their crystal structure, they are easier to
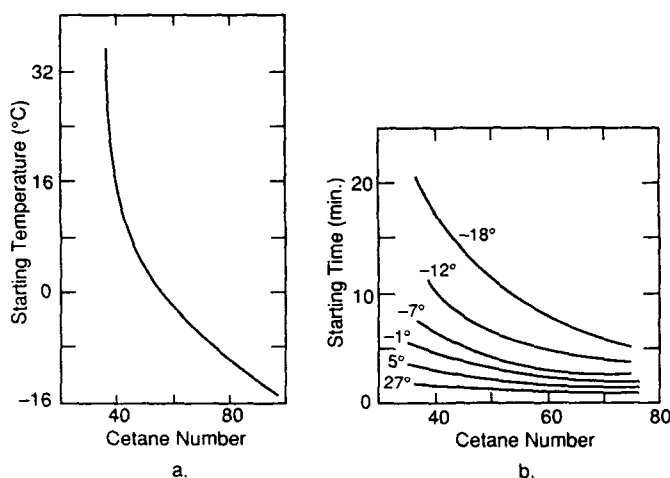
5. *Effect of cetane number on engine starting. (After Smolin 1908.) a. Effect of cetane number on the temperature at which an engine will start relatively easily (within 5–10 minutes). b. Effect of cetane number on the starting time at temperatures between –18° and 27°C.*

pump at temperatures down to their pour point than are partially solidified naphthenic fuels because the crystals tend to slide over one another, while the heavier naphthenic compounds resist such movement.

The minimum cetane number for direct-injection engines should be 40. This is the cetane number specified in the ASTM standards for diesel fuel 1-D and 2-D and by MILSPEC for DF-A. Engines with precombustion chambers will tolerate cetane numbers down to 35. Generally an increase on the order of 10 in the cetane number will lower the temperature at which the engine can be started and will decrease the starting time as shown in Figure 5. Such an increase has little effect on engine performance in subsequent normal operation. The cetane number of a fuel can be increased either by mixing it with another fuel with a higher cetane number or by using a cetane improver additive.

Because diesel fuels are drawn from compounds with such a wide range of boiling points, they will contain some high-molecular-weight hydrocarbons whose melting points are quite high. When the temperature falls below their melting points, they will tend to crystallize, forming suspended particles of paraffin wax in the fuel.

Waxes are present in all diesel fuels to some extent. DF-2 (No. 2-D diesel fuel) may contain 6–8% wax. In temperate areas these waxes are not a problem as they are easily held in solution in these relatively warm conditions; in fact, they exert a beneficial effect on the fuel, improving the ignition quality, pumpability and heat content. However, at low temperatures the waxes come out of

Wax formation and cloud point

solution, forming crystals that impart a cloudy appearance to the fuel. The temperature at which this begins to happen is the cloud point. When this point is reached, the fuel filter tends to become clogged and eventually the engine becomes starved of fuel and quits. The best remedy for this is to replace the fuel filter and heat the fuel tank in extreme cases or at least the filter or fuel line upstream of the filter.

The cloud point of DF-2 is about −10°C. It can be lowered by combining the diesel fuel with another fuel with a lower wax content, such as kerosene; however, for practical purposes, DF-2 is seldom used in extremely cold regions since such a blend would have to contain almost exclusively kerosene to dissolve the remaining waxes in the DF-2 at the extremely low temperatures often encountered. DF-1 is commonly used, but DF-A is usually the fuel of choice in areas where temperatures are frequently below −40°C.

In areas where the temperatures may be low enough to cause waxing problems in diesel fuels but not low enough to justify the exclusive use of kerosenes, diesel fuel and kerosene are commonly blended. Since all of the kerosene turbine fuels and much or all of the lighter diesel fractions, including DF-A, are derived from the same fraction of the crude barrel, there may be a shortage in some areas of suitable low-temperature fuels with which to cut the heavier diesel fuels, which are available. In this case it may be wise to blend the fuel on site on a daily basis. In this way the scarce (and usually expensive) kerosene supply can be stretched. Usually fuels are blended at the terminal using the lowest expected temperature for the month as a guide for the appropriate mix. However, this minimum temperature may only be encountered a few days out of the month, which means that a great deal of kerosene will be used needlessly. Therefore, mixing the fuels on site on an as-needed basis may result in considerable cost savings. Appendix A gives a simple method of determining the proportions of No. 2-D diesel fuel and kerosene needed for a suitable low-temperature mix. The cloud points required for the calculation must be obtained from the fuel supplier.

Gasoline should never be added to diesel fuels, as the much higher vapor pressure of the resulting blend may constitute a serious fire hazard. In addition the use of gasoline in diesel engines may cause preignition due to static discharge within the cylinder, resulting in potential engine damage as well as other types of abnormal combustion conditions.

Solidification and pour point   Diesel fuels at their pour points will barely flow. However, at temperatures between the pour point and the cloud point, they can

be pumped using suitable equipment. This is significant from the standpoint of refueling, as most properly winterized equipment will possess heaters for the fuel filter or fuel line or both, making it possible to use this highly viscous fuel.

At very low temperatures the viscosity of diesel fuel increases such that the fuel quantity, the range of injection (the distance that spray penetrates the combustion chamber) and the degree of atomization (droplet size) are seriously reduced. This is especially pronounced during cranking and low-speed operation, and it greatly hampers effective delivery of fuel to the combustion chamber. A sufficient degree of atomization of fuel may be achieved if the fuel viscosity does not exceed about 100 cs.

Excessive viscosity

The worst problem caused by sulfur in the fuel is corrosion, which results especially under conditions of excessive idling common in extremely cold areas. This is because combustion products and unburned fuel have a greater tendency to bypass the cylinders and contaminate the engine oil in the crankcase with sulfur compounds, water, soot, etc. The resulting sludge is highly corrosive, especially to parts made of brass, bronze or copper. In these conditions the engine oil must be changed frequently.

Sulfur

A very small amount of condensed moisture or water in the fuel system can form a clog upon freezing. To minimize condensation in the fuel tank, it should be kept as full as possible, particularly when parked overnight. The use of oversize fuel lines and fittings smoothly rounded inside is added insurance. Drain cocks in the fuel tank should be used from time to time, and settling bowls in the filter housing should be periodically checked for accumulated water and emptied when necessary. Some fuel filters are designed to remove water as well as other contaminants. All fuel filters will remove water in the form of ice crystals and can easily become clogged if excessive quantities are present.

Water contamination

Alcohols may be used in diesel fuels as in gasoline to dissolve small amounts of suspended water. The proportion of alcohol to fuel should not be greater than 0.1% (about 10 oz. in 75 gal. of fuel or 100 mL per 100 L). A larger amount may lower the flash point of the fuel, creating a fire hazard. Ethylene glycol monomethyl ether has also been used with success in diesel fuel, but the proportion used is more critical than for the alcohols. Excessive use may corrode the injectors or clog the injectors and pumps or both. This is the icing inhibitor of choice of the U.S. Army, which recommends the addition of 1 pint in 40 gal. of fuel (about 300 mL per 100 L).

This material should be used with care, as it is more toxic than the alcohols and readily absorbed through intact skin.

Fuel filters   In general, fuel filters are necessary to prevent small particles of rust or other such debris from clogging the fuel injectors or other small tubes and orifices. The best choice of filter is the one recommended by the manufacturer. However, extremely low temperatures impose an abnormal load on the system in the form of wax, water or ice particles, which will not in themselves cause engine damage but may form constrictions in the fuel supply lines and will certainly clog the fuel filter. Therefore, some accommodation may have to be made for cold conditions, ideally after consultation with the equipment manufacturer.

Water can be removed by pumping fuel through a combined fuel filter and water separator. Although this can only be done while the engine is running, it has a very great impact on subsequent vehicle starting. Fuel filter and water separator units are available that are claimed to remove virtually all water as well as contaminants down to a very small size. Using one of these units will not only improve the quality of the fuel used for combustion but, due to the large volume of fuel that is recirculated, will also reduce the amount of water and other contaminants throughout all parts of the fuel system. By routing the fuel return line alongside the fuel supply line and covering the two in common insulation, incoming fuel can derive some heat from the warm fuel returning to the fuel tank. Filters that remove very small particles can be used in cold regions, but it is necessary to accompany a fine filter with a system that warms the fuel so that wax and ice crystals cannot form and clog the filter. Heating also increases the amount of water that the filter will be able to extract.

As an alternative or addition to fuel warming, there are a variety of flow improvers that can be added to the fuel to reduce the size of wax crystals. By warming fuel and removing excessive water and contaminants associated with fuels at low temperatures, problems with injectors will be virtually eliminated. Another method, used with success by the Soviets, is a system that uses an injector with two settings, one for warm weather, the other for cold.

A final variant on the fuel filter theme is a system with a bypass such that when the filter becomes clogged, the fuel will be carried directly to the engine without filtering. These systems are available with a warning light so that the operator is aware that the filter is not operating. This arrangement is very convenient from the standpoint that the equipment will not quit somewhere far from the repair facility. However, the filter should be replaced without delay as the

lack of filtration may result in particles, which the filter was designed to exclude, getting into the injector system and plugging the nozzles or other small passages.

Priming with a highly volatile fuel is a fairly common practice, commercially and militarily, to start cold engines. This is done with both compression and spark ignition engines, although the benefit is greater with compression engines. Priming is merely injecting diethyl ether into the engine intake manifold. The priming fuel, having a much wider flammability range than pure hydrocarbons, ignites and burns much more readily than the regular fuel under the adverse combustion chamber conditions prevalent in cold engines. The combustion chamber needs only to reach 185°C to ignite ether, whereas diesel fuel requires 340°C. Other ingredients of the priming fuel provide initial top-cylinder lubrication and improve the fluid's storage stability. Most major diesel equipment is supplied with ether injection systems. The use of ether primers should not be necessary in smaller diesel equipment such as pick-up trucks or in spark ignition engines.

Ether starters

In spite of the apparent advantage of using ether as a cold-starting aid, there is a large and growing body of opinion against its use. Ether injection is commonly associated with the dissolving of lubricating oil around the cylinder walls and piston rings, with resultant engine wear. Furthermore, it may ignite too soon in the combustion cycle, causing knocking, which results in great strain and potentially severe damage to the rods and other engine parts. Too much ether causes excessive pressure in the combustion chamber and can lead to cracked piston ring landings, blown-out head gaskets, stretched head bolts, damaged valves, broken pistons, etc. The increased brittleness of metals at very low temperatures exacerbates the problem. At temperatures below -20°C, the use of ether may result in the breakdown of up to 40% of the equipment using it. WD-40 (a low-viscosity penetrating oil) or similar compound is often used instead of ether and is thought to be less injurious to the engine. The Soviets utilize sealed ampules and a compressed air tank for injecting Kholod-D-40, a mixture of 60% ether, 15% gasoline, 15% isopropyl nitrate and 10% low-viscosity lubricant. They claim that injection of this mixture increases startability and that there is negligible resultant engine wear.

Priming systems commonly used in the United States consist of a dispenser assembly for holding and puncturing the capsule, tubing, and a pump for forcing a measured amount of ether through a nozzle into the engine intake manifold. The amount of ether injected is sometimes controlled to prevent use of excessive amounts.

6. Number of mea-
sured doses of ether
required to start a
cold-soaked engine at
low temperatures.
(After Stupich 1987.)
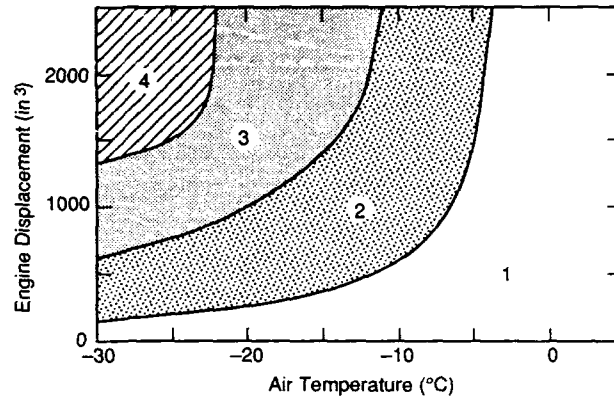
However, the optimum dosage is not equal under all circumstances. The ether requirement increases with decreasing temperature, as shown in Figure 6. The required dose may not be the same for all equipment, and overuse or misuse in inexperience hands may result in the problems mentioned above. The use of measured-dose systems will minimize (but probably not eliminate) the amount of engine damage resulting from the use of an ether starter if the engine manufacturer's guidelines are strictly adhered to. The key is to use as little ether as possible. For this reason the use of unregulated doses from spray cans commonly available in auto parts stores should be strongly discouraged, as the tendency is to use too much.

While some equipment is designed for use with ether starters, others are not (for example, Caterpillar approves of the use of ether in its direct injection engines but not in those with precombustion chamber fuel injection systems). After-market ether injection systems are available but should be used with great care if at all. Experienced operators have observed that once ether has been used in an engine, starting becomes difficult or impossible without it. This may be due to minor damage to the cylinder walls caused by dissolution of the protective lubricating layer by the ether, followed by scoring and a consequent decrease in compression. The best approach seems to be not to use it at all unless absolutely necessary. It is far safer to heat the engine until it will start without the use of ether. If this is ineffective, the engine may need repair, new lubricant, new battery or other remedial measures.

If an ether starting system is to be used, the following precautions should be taken:

- NEVER use ether in an engine with glow plugs, plasma plugs or electrical resistance heaters in the intake manifold. This can cause serious explosions, resulting in equipment damage and personal injury.

- Ether is poisonous. Breathing its vapors or repeated contact with skin can cause injury. Use ether only in well-ventilated areas.
- Ether is highly flammable. Do not smoke while using or changing ether cylinders.
- Do not store ether cylinders in the operator's compartment or living areas. Do not store cylinders in direct sunlight or at temperatures above 49°C.
- Discard ether cylinders properly—do not puncture or burn them.

It is a good idea to store fuel outside. Aside from being generally safer, any water present will freeze after separating from the fuel and will not contaminate vehicle fuel tanks. Also, any low-temperature effects such as clouding or solidification will be apparent before the fuel is in the equipment, so that remedial action can be taken. This is especially important in the case of heavier diesel fuels, whose low-temperature characteristics can be improved through the addition of kerosene.

Material compatibility and fuel storage

When ambient temperatures are above freezing, it is a good idea to drain off any accumulated water. This will prevent corrosion of the tank and contamination of the fuel by rust or other particles that may have collected in the bottom of the tank.

Fuels may degrade during storage through breakdown of unstable constituents (e.g. olefins) and through reaction with materials in the storage system, such as noncompatible metals and some nonmetals, such as certain elastomers used in gaskets and seals. Table 2 indicates metals that are suitable and others that are unsatisfactory for use with hydrocarbon fuels. Fiberglass is a good material for storage tanks as it will eliminate problems with rust

Table 2. Acceptable and unacceptable metals that may exist in fuel storage systems. (After Coordinating Research Council, Inc., SAE 1983.)

Satisfactory	Unsatisfactory
Aluminum and all its alloys	Bronze
Carbon molybdenum steel	Nickel
0.5–3% nickel steel	Copper
4–6% chromium molybdenum steel	Zinc
300 and 500 series stainless steel	Cadmium
Monel	Brass

Table 3. Some commercially available materials suitable for use for seals and O-rings to be used in fuel systems at low temperatures. Other low-temperature materials are available but are not suitable for use with petroleum oils. The breadth of the low-temperature range is due to the variability in the composition of the compounds as well as to the application. A seal will often serve to a lower temperature in a static application than in a dynamic one.

Material	Diesel fuel	JP-8	JP-5	JP-4	Gasoline	Water	Low-temperature bound ($^{\circ}C$)
Nitriles, e.g. Krynac, Hycar, Chemigum	OK	OK	OK	OK	OK	OK	−40 to −54
Flourosilicones, e.g. Silastic	OK	OK	OK			OK	−50 to −73
Fluorocarbons, e.g. Kel-F, Fluorel, Viton, Teflon	OK	OK	OK	OK	OK		−40 and below
Nylon	OK	OK	OK	OK	OK	OK	−54

from water in the fuel and from groundwater if the tank is buried. Galvanized tanks should never be used.

At extremely low temperatures, metals become very brittle, and above-ground storage tanks may be subject to mechanical damage if they are struck or jostled. Welded seams and joints are especially vulnerable. Therefore, such tanks should be protected as much as possible with a railing, and caution should be exercised when maneuvering vehicles in their vicinity.

Table 3 shows a number of materials commonly used in the manufacture of seals for low-temperature applications and their compatibility with various fuels and with water. O-rings and seals composed of nitriles, fluorocarbons and fluorosilicones are commercially available for most applications and are commonly designed for use down to at least −40°C. Nitriles are probably the most common compounds used in seals because of their good resistance to petroleum oils and their wide temperature range. Unfortunately, in compounding for improved low-temperature performance, some petroleum oil resistance is lost, which may lead to early degradation of the seal. Therefore, a fluorosilicone or similar material would probably be a better choice, especially at extremely low temperatures. Silicone rubbers remain flexible down to very low temperatures but are not suitable for use with petroleum fuels. Nylon and Teflon are commonly used as backup rings to give skeletal strength to some seals. This becomes increasingly important in low-temperature applications since many of the compounds used for the primary seal are relatively soft and are prone to excessive abrasion and similar damage.

It is a good idea to use low-temperature-resistant hoses not only on vehicles but also in the fuel delivery system. A hose below its low-temperature limit will become too rigid to use, and in the worst case it will be so brittle that it will break at any attempt to flex it.

In general, if suitable precautions are taken, fuels should not be **Conclusions** a major source of low-temperature problems in automotive operations. If care is taken to exclude water from storage tanks and vehicle fuel tanks, the addition of small amounts of anti-icing compounds to the fuel should be sufficient to eliminate blockages due to icing of fuel lines and filters.

Gasoline in itself should be trouble free if a suitable winter blend is used, and many of the low-temperature problems associated with diesel fuels can be reduced or eliminated through the use of fuel-line and fuel-filter heaters in conjunction with the use of a suitable fuel blend.

There are numerous advantages to using highly refined kerosene-type jet fuels over diesel fuels:

- They have superior low-temperature properties, including lower cloud and freeze points and improved cold-starting performance.
- They burn more cleanly than diesel fuels and therefore produce fewer emissions.
- Component wear related to engine combustion byproducts is reduced.
- Nozzle fouling and deposit problems in both diesel and gas turbine engines are reduced.
- Fuel and oil filter replacement intervals are increased, as are oil change intervals.
- The potential for fuel system corrosion problems is reduced.

Many of these benefits are due to the lower sulfur and ash content of these highly refined fuels.

On the other hand, fuel consumption may increase up to about 5% due to the lower energy content of kerosene fuels over diesel, and fuel injection pumps on some equipment may experience increased wear due to the lower viscosity, resulting in further power loss. However, these disadvantages are a small price to pay for the improved operability resulting from the use of these fuels.

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**Appendix A:
Estimating the
fuel blend cloud
point from the
cloud point blend-
ing indices (CPI).
(After Mobil 1989.)**

To determine the blend composition to make a specified cloud point:

$$K = 100 \times \frac{(B-A)}{(B-C)}$$

where K = kerosene in the blend (%)
B = cloud point index (CPI) of diesel fuel in the blend
A = CPI of the desired blend
C = CPI of kerosene.

For example, how much kerosene is needed in a No. 2-D diesel fuel to make a fuel blend whose cloud point is –18°C? The cloud point of the No. 2-D diesel fuel is –14°C and the cloud point of the kerosene is –38°C. Read the CPI values from Table A1 and substitute them in the equation:

$$K = 100 \times \frac{(62-48)}{(62-11)}$$

$$= 100 \times \frac{(14)}{(51)}$$

$$= 27\%.$$

The fuel blend composition is 27% kerosene and 73% No. 2-D diesel fuel.

To determine the cloud point of a fuel blend:

$$A = \frac{D}{100} (B) + \frac{K}{100} (C)$$

where A = cloud point index (CPI) of the blend
D = No. 2-D diesel fuel in the blend (%)
B = CPI of No. 2-D diesel fuel
K = kerosene in the blend (%)
C = CPI of kerosene.

For example, a No. 2-D diesel fuel whose cloud point is –12°C is blended with a kerosene having a cloud point of –40°C. The blend contains 70% of the diesel fuel and 30% of the kerosene. What is the cloud point of the blend? From Table A1, the CPI of the diesel fuel is 73 and the CPI of the kerosene is 9. Substitute those numbers in the equation as follows:

$$A = \frac{70}{100} (73) + \frac{30}{100} (9)$$

$$= 51.1 + 2.7$$

$$= 53.8.$$

Using this value for A, read the blend cloud point from the table; the cloud point is $-17°C$.

Table A1. Cloud points and cloud point indexes.

Cloud point (°C)	CPI
5	240
3	226
2	213
1	200
0	187
−1	172
−2	158
−3	147
−4	135
−6	124
−7	114
−8	105
−9	96
−10	88
−11	81
−12	73
−13	67
−14	62
−16	57
−17	53
−18	48
−19	45
−20	41
−21	37
−22	34
−23	31
−24	28
−26	26
−27	25
−28	23
−29	21
−30	19
−31	17
−32	16
−33	15
−34	14
−36	13
−37	12
−38	11
−39	10
−40	9
−41	8
−42	7.5
−43	7
−44	6.5
−46	6
−47	5.5
−48	5